

PULSE SHAPING FOR LOCALIZED MAGNETIC RESONANCE TAGGING

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Abstract- Magnetic resonance tagging is usually achieved by means of a train of non-selective radio-frequency pulses separated by gradient pulses. Thus, the modulation of the M_z magnetization component expands all over the imaging plane. It has been proposed that the use of selective excitation pulses may limit the modulation only to regions of interest, thus preserving anatomical data in the rest of the image. In this paper, we intend to expand the tagging k-space concept in order to account for pulse selectivity, and offer a prediction and design tool for localized MR tagging sequences.

Keywords - Magnetic resonance tagging, tagging k-space, selective excitation, variable tagging sequences

I. INTRODUCTION

Magnetic resonance tagging is based on embedding, by means of an appropriate pulse sequence, a grid of magnetically saturated planes perpendicular to the imaged one. During imaging, these planes form a varying brightness grid, and their deformation over time may be used to assess tissue motion [1].

The grid is produced by means of a specially designed sequence, that consists of alternating radio-frequency and gradient pulses. In its simplest form, as in the SPAMM 1-1 sequence [2], tagging is achieved by two non-selective rf pulses separated by a gradient pulse. Plane selection is made by phase-encoding the transverse magnetization component produced after the first rf pulse, that differentiates the populations' response to the second rf pulse corresponding to their position with regard to the encoding gradient. Thus, whilst for certain populations the two rotations add, for others they subtract and in overall they form a sinusoidal distribution that covers the whole imaging plane.

More sophisticated versions of the SPAMM sequence [3] consist of a longer train of alternating rf and gradient pulses, aimed at producing a sharper tagging pattern. However, the pattern is still uniform and due to the discreteness introduced by the well separated non-selective pulses, it keeps repeating all over the imaged plane.

Non-uniform tagging patterns have gained interest lately, since they are better suited to non-uniform anatomies. Sequences proposed [4,5] are based on selective excitation concepts [6], while consisting themselves of non-selective rf pulses alternating with gradient pulses. These sequences offer a sharp tagging grid that can be adjusted to the anatomy studied by means of variable grid separation. However, complexity rises and the pulse trains are considerably longer, consisting of up to several tens of pulses. Thus rapid gradient switching poses a limit to the sequence's speed.

Furthermore, in all the abovementioned techniques the grid expands all over the imaged plane. This is not always necessary or desirable, since in many cases the motion to be studied is confined to a certain region of the image. In this

case, the rest of the grid hides anatomical information that might be of value. Preservation of this information is achieved in the CSPAMM technique [7], where two acquisitions are used in order to achieve an enhanced tagging grid and an image without tagging simultaneously. It has also been proposed [8], that the combined application of selective excitation pulses in tagging sequences can confine the tagging grid to only a region of interest, in the so-called localized tagging experiments.

Indeed, the use of selective excitation pulses offers an attractive enhancement to tagging sequences. Selective pulses may enhance the sequence's selectivity, by defining a region of interest (ROI), and confining the tagging grid to it. Thus, anatomical information outside this ROI is preserved. A more subtle advantage is that of eliminating the need for gradient switching, thus relieving time constraints and patient exposure to alternating fields.

In this study, we intend to enhance the tagging k-space concept introduced in [5], in order to provide a mathematical framework for the use of selective excitation pulses in one-dimensional tagging experiments. This leads to a very simple relationship between the pulse shape and the regions where the tagging is preserved. Based on this concept, we investigate both the error introduced by keeping the gradient constant in usual tagging sequences, as well as the selectivity enhancements possible considering the type and the length of the tagging sequence. We believe that the insight gained by the mathematical analysis may be used to enhance the tagging sequence design process.

II. THEORY

Tagging k-space [5] offers a robust framework for describing and analyzing tagging sequences. It is based on the k-space approximation for small-tip-angle excitation [6], thus taking advantage of the Fourier relationship between excitation and magnetization profile and offering a simple mathematical framework.

Prediction of the tagging pattern is based on the k-space path of the pulse sequence:

$$p(\mathbf{k}) = \int_0^T B_1(s) \mathbf{d}(\mathbf{k}(s, T) - \mathbf{k}) ds, \quad (1)$$

$$\text{where } \mathbf{k}(s, t) = -\mathbf{g} \int_s^t \mathbf{G}(u) du \quad (2)$$

B_1 being the radiofrequency waveform, \mathbf{G} the gradient, \mathbf{g} the gyromagnetic ratio and \mathbf{d} the delta function.

Alternating rf and gradient pulses have the effect of transforming the rf pulses in delta functions in the k-space path: During the application of the pulse, there is no

Report Documentation Page

Report Date 25 Oct 2001	Report Type N/A	Dates Covered (from... to) -
Title and Subtitle Pulse Shaping for Localized Magnetic Resonance Tagging		Contract Number
		Grant Number
		Program Element Number
Author(s)	Project Number	
	Task Number	
	Work Unit Number	
Performing Organization Name(s) and Address(es) Telecommunications Division Department of Electrical and Computer Engineering Faculty of Technology Aristotle University of Thessaloniki, 54006 Thessaloniki, Greece		Performing Organization Report Number
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500		Sponsor/Monitor's Acronym(s)
		Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited		
Supplementary Notes Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.		
Abstract		
Subject Terms		
Report Classification unclassified	Classification of this page unclassified	
Classification of Abstract unclassified	Limitation of Abstract UU	
Number of Pages 4		

evolution of the k-space path and thus each of them is applied in a well-defined single point of k-space.

Selective excitation pulses cannot be represented as delta functions, since they consist of a simultaneous application of gradient and radio-frequency radiation. If we consider the gradient to be kept constant throughout the pulse sequence, the k-space path keeps evolving during the time we apply the rf pulse, and thus the pulse's energy is applied to a continuous area of k-space around the point of the original delta function, producing a dispersion effect. The type of the dispersion depends on the pulse's envelope, and may be described as the individual pulses k-space path:

$$p_p(\mathbf{k}) = \int_0^{T_p} B_1(s) d(\mathbf{k}(s, T_p) - \mathbf{k}) ds \quad (3)$$

where T_p denotes the individual pulse's duration.

Uniform gradient ensures a uniform k-space evolution in time. Assuming that envelope shape of all pulses is identical, and if the k-space path of the idealized (alternating RF and gradient pulses) sequence is given by $p_s(\mathbf{k})$, then the final k-space path will be given by

$$p(\mathbf{k}) = p_s(\mathbf{k}) * p_p(\mathbf{k}) \quad (4)$$

where the asterisk (*) denotes convolution.

Finally, the longitudinal magnetization M_z is given by:

$$\begin{aligned} M_z &\approx 1 - \frac{1}{2} \left| \mathbf{g} \int_{\mathbf{k}} p(\mathbf{k}) e^{i\mathbf{x} \cdot \mathbf{k}} d\mathbf{k} \right|^2 \\ &= 1 - \frac{1}{2} \left| \mathbf{g} \int_{\mathbf{k}} (p_s(\mathbf{k}) * p_p(\mathbf{k})) e^{i\mathbf{x} \cdot \mathbf{k}} d\mathbf{k} \right|^2 \end{aligned} \quad (5)$$

Using the well-known modulation property of the Fourier transform [9], this becomes:

$$M_z \approx 1 - \frac{1}{2} \left| \mathbf{g} \left(\int_{\mathbf{k}} p_s(\mathbf{k}) e^{i\mathbf{x} \cdot \mathbf{k}} d\mathbf{k} \right) \cdot \left(\int_{\mathbf{k}} p_p(\mathbf{k}) e^{i\mathbf{x} \cdot \mathbf{k}} d\mathbf{k} \right) \right|^2 \quad (6)$$

Thus, we see that the final M_z pattern will be modulated by the square of the Fourier transform of the pulse's envelope.

In order to evaluate the envelope's effect on the tagging pattern, it is necessary to estimate the spectral occupancy of the tagging grid and the envelope.

The tagging grid is formed by a periodic spatial repetition of a main tagging pattern. This periodicity is defined by the rotation induced by the gradient in the time interval between two subsequent pulses: the tagging pattern repeats itself for populations for which the respective rotations differ by even multiples of δ . Thus, the longer the interval between two subsequent pulses, the closer the repetitions of the tagging pattern.

One may distinguish between two different applications of the preceding analysis. The first deals with constant gradient tagging, where one wants to minimize the effects of keeping the gradient constant during the pulse sequence. Since the envelope's spectral width may be roughly estimated as the inverse of its duration, depending of course on the

actual waveform, this problem calls for short pulses with wide spectral content. The second deals with exploring the individual pulse's selectivity in order to enhance, or the tagging grid, possibly over several repetitions of the tagging grid. In any case, the extent of the envelope's effects and the amount of "usable" tagging pattern repetitions are largely dependant on the relationship between the duration of the individual pulse and the time between two subsequent pulses: the shorter the pulse, or the longer the time between two subsequent pulses, the closer we are to the ideal case of subsequent RF and gradient pulses.

III. RESULTS

A. Selectivity enhancement

Enhanced selectivity is usually desired in simpler pulse sequences, whose final grid consists of several repetitions of an original small uniform grid.

In order to test the accuracy of the analysis, we tested its predictions on a SPAMM 1-1 [2] and a SPAMM 1-2-1 [3] sequence, using sinc-shaped pulses in order to produce the selectivity effect. The tagging sequences are shown in figures 1 and 2. No spoiler or refocus gradients are used, thus avoiding overall gradient switching.

Testing was performed both by simulation on 4096 distinct magnetic populations, using a hard-pulse approximation, and by experiment on our experimental custom-made 0.12 T magnetic resonance scanner.

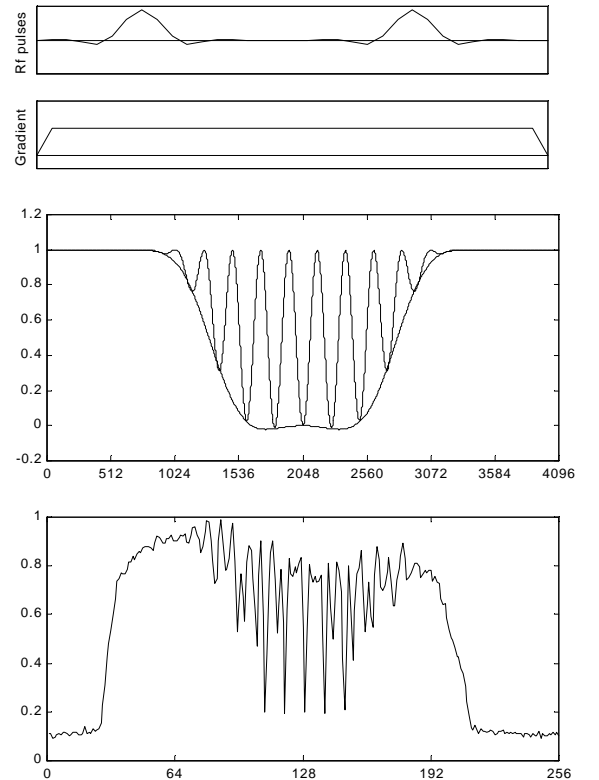


Fig. 1. Tagging sequence simulated and measured tagging profile for a SPAMM 1-1 sequence implemented using windowed sinc pulses. In the upper figure, the dashed line shows the predicted envelope, while the solid line shows the simulated tagging pattern.

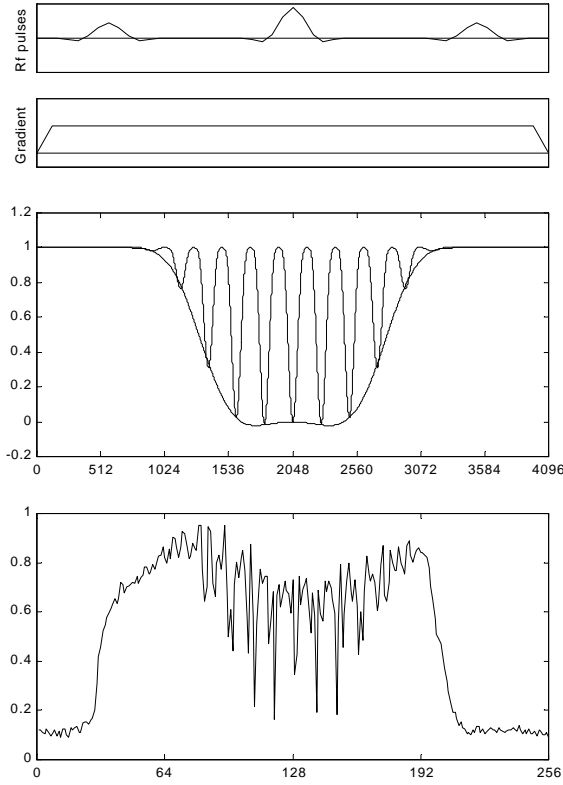


Fig. 2. Tagging sequence, simulated and measured tagging pattern for a SPAMM 1-2-1 sequence implemented using windowed sinc pulses. The dashed line shows the predicted envelope, while the solid line shows the simulated tagging pattern.

The results show that the envelope's prediction is reasonably accurate. Deviations in the measured pattern are expectable due both to errors in the measurement of the flip angle and to the low signal-to-noise ratio.

B. Error estimation for constant gradient application

In the case of the newer variable tagging sequences, selectivity enhancement is not of prime interest, since in most cases the image is covered from a single or a few repetitions of a tagging grid pattern that fit optimally the studied anatomy.

One problem faced with these sequences though is that they consist of long pulse trains. Switching the gradient on and off poses limits to the sequence's speed, making in some cases its application not practical.

In the following examples, we estimate the error introduced by replacing the non-selective rf pulses by short selective ones in the presence of a constant gradient. The aim is not to enhance the selectivity, but to provide an acceptable alternative to gradient switching.

Rectangular pulses are the easiest to implement, and a natural first choice. For testing, we chose a 26-pulse variable tagging sequence, with the grid forming from several repetitions of an original 3-line pattern. We tested the impact on the tagging pattern for pulse duration accounting for the 22% of the time between pulses. Both simulation and measurement results are shown in figure 3. We see that the

tagging pattern follows well the anticipated $\text{sinc}^2(x)$ pattern that is predicted by the Fourier transform of the pulses' envelope.

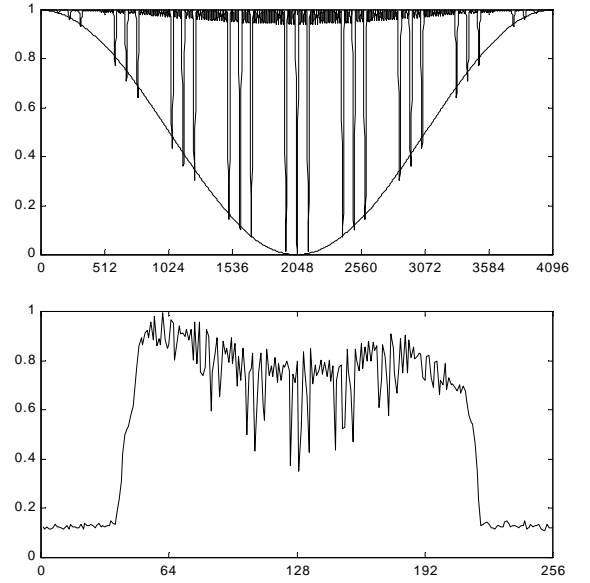


Fig. 3. Simulated and measured tagging pattern for a 26-pulse SLR [9,10] variable tagging sequence implemented using rectangular shaped pulses.

In order to minimize the effects, whilst keeping relatively long duration for the individual pulses, one might choose pulse envelopes with smooth and wide spectral characteristics. Gaussian pulses offer a popular solution. Results for gaussian shaped pulses with duration amounting for 55% of the time interval between two subsequent pulses are shown in figure 4.

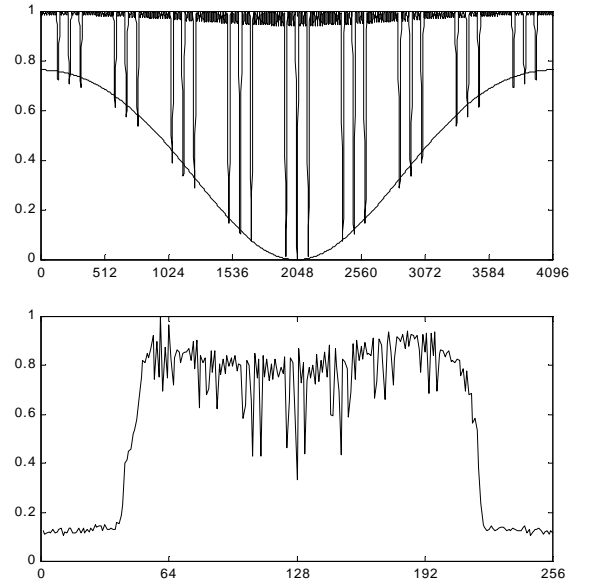


Fig. 4. Simulated and measured tagging pattern for a 26-pulse SLR variable tagging sequence implemented using gaussian shaped pulses.

As we can see, the actual pattern follows well the predicted envelope (dashed line). The small deviations in the simulated results can be attributed to numerical errors.

The main advantage of the proposed pulse sequences is the speed that was limited only by the desired distance between the tagging pattern repetitions. Thus, tagging times of below 5 ms for a 26-pulse sequence are achievable.

IV. DISCUSSION

There are two main fields of interest for the application of selective pulses in magnetic resonance tagging.

The first one addresses limiting the tagging grid only to the region of interest. This will help to preserve anatomical information in the rest of the image plane. The preceding analysis, based on simple Fourier relationships, shows that this is possible in cases where the grid consists of several repetitions of a simple pattern, like in the case of the SPAMM techniques presented above.

One could consider the use of more complicated, optimized pulses in order to produce variable tagging sequences. In this case, the grid variability will be based on the pulse's ability to select (or un-select) specific, possibly several regions of the image where the grid is to be applied, whilst preserving anatomical information in the rest of the image.

The second field of interest is the investigation of the possibility to use constant gradient during the application of the tagging sequence. Here, the interest lies not in enhancing the selectivity, but in minimizing the error introduced by it.

This consideration is of particular importance in the case of the newer variable tagging sequences. These consist of long trains of alternating rf and gradient pulses. As the sequence gets more sophisticated, the better approximation usually demands a longer pulse train, thus posing a time limit to the approximation due to the gradient switching involved. Thus, a constant gradient may offer a solution for faster variable tagging sequences.

On the other hand, in variable tagging sequences one is usually interested in a single, the central repetition of the tagging pattern. From the examples presented it shows that the error involved in this repetition is minimal, since for the cases discussed the envelope's peak spectral power lies in the same spectral region. By selecting an appropriate pulse shape, one can considerably limit the error over several repetitions, while allowing sufficient time for the rf pulse to evolve. The latter consideration limits peak rf power and the strain on the rf system.

Summarizing, in either case one may consider tagging sequence design as a two step process: one may first select the main tagging sequence and tagging pattern that is appropriate for the application at hand, and then select a pulse that either adds selectivity or minimizes the approximation error.

V. CONCLUSION

We have presented an extension to the tagging k-space concept that can be used to account for use of a uniform train of selective rf pulses and a constant gradient during the application of a magnetic resonance tagging sequence. The extension leads to a simple convolution between the idealized

tagging pattern and the pulse's spectrum, thus offering valuable insight on the pattern's deformation.

The results of the analysis were tested on localized SPAMM sequences, as well as on variable tagging sequences. We demonstrated that the use of constant gradient may be exploited either for the production of a selectivity effect, due to the selectivity of the rf pulses involved, or simply for making a faster sequence, by avoiding the gradient switching.

Thus, the analysis may be used to design simple localized tagging sequences, or to predict the error introduced by constant gradient application during the tagging sequence. In either case, one may choose the appropriate pulse shape to achieve the wanted selectivity or to minimize the error, depending on the application at hand.

REFERENCES

- [1] E. A. Zerhouni, D. M. Parish, W. J. Rogers, A. Yang, E. P. Shapiro, "Human heart: tagging with MR imaging - a method for noninvasive assessment of myocardial motion." *Radiology* pp.59-63, vol 169, 1988
- [2] L. Axel, L. Dougherty, "MR imaging of motion with spatial modulation of magnetization." *Radiology* pp. 841-845, vol 171, June 1989
- [3] L. Axel, L. Dougherty, "Heart Wall Motion: Improved Method of Spatial Modulation of Magnetization for MR Imaging", *Radiology*, pp. 349-350, vol. 172, August 1989
- [4] E.R. McVeigh and B.D. Bolster Jr., "Improved Sampling of myocardial motion with variable separation tagging", *Magn. Reson. Med.*, pp. 657-661, vol. 39, 1998
- [5] W.S. Kevin, J.L. Prince, "A k-space Analysis of MR Tagging", *J. Magn. Reson.*, pp. 313 - 322, vol. 142, 2000.
- [6] J. Pauly, D. Nishimura and A. Macovski, "A k-space analysis of small-tip angle excitation", *J. Magn. Reson.* pp. 43-56, vol. 81, 1989
- [7] S. E. Fisher, G. C. McKinnon, S. E. Maier, P. Boesiger, "Improved Myocardial Tagging Contrast", *Magn. Reson. Med.*, vol. 30, pp. 191-200, 1993.
- [8] S. Chandra and Y. Yang, "Simulations and Demonstrations of Localized Tagging Experiments", *J. Magn. Reson. Ser. B*, vol. 111, pp. 285-288, June 1996.
- [9] J. Pauly, P. Le Roux, D. Nishimura and A. Macovski, "Parameter Relations for the Shinnar - Le Roux Selective Excitation Pulse Design Algorithm", *IEEE Trans. Med. Imag.*, vol. 10, pp. 53 - 65, 1991.
- [10] M. Shinnar and J.S. Leigh, "Inversion of the Bloch equation", *J. Chem. Phys.* pp. 6121- 6128, vol. 98(8), 1993